PROGRAMMED PILOTAGE AS A MEANS OF IMPROVING ROTORCRAFT PERFORMANCE IN LEVEL FLIGHT

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THESIS

PROGRAMMED PILOTAGE AS A MEANS
OF IMPROVING ROTORCRAFT PERFORMANCE
IN LEVEL FLIGHT

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Programmed Pilotage as a Means of Improving Rotorcraft Performance in Level Flight

by

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Lieutenant, United States Navy
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ABSTRACT

Considerable effort and money have been expended on research relating to the next generation of STOL/VTOL aircraft. Since the helicopter offers many advantages not attainable in other direct lift aircraft, expansion of its translational speed range represents an excellent means of improving its competitive position.

Airframe drag reduction and engine duct design, while necessary to the improvement of performance, cannot alone offset the aerodynamic limitations inherent in rotary wing flight. The latter, which have become predominant with the advent of high output turboshaft engines must then be overcome by other means discussed in this paper. Programmed pilotage techniques which utilize real-time flight data to vary aerodynamic parameters are investigated and incorporated in the preliminary design of a high-speed rotorcraft. The rotor speed and the contribution of lift from a fixed wing are thus optimized throughout the flight envelope, thereby greatly enhancing level flight speed characteristics.

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I. INTRODUCTION

Programmed pilotage is the technique of automatically altering flight parameters during flight to optimize performance. This loose definition fits a full spectrum of systems and devices as diverse as autopilots and fuel controls and includes the ramp intakes and wing-swing program on the F-14 airplane.

Helicopter performance was limited in the past by power plant capability. The hover mode received the lion's share of attention and fuselage and rotor design reflected this attitude. With the advent of the turboshaft engine, power available took a substantial step forward. Unfortunately, the fuselage and rotor design remained essentially unchanged. The results have been far from optimal.

Compounding, i.e., addition of wings and auxiliary thrust devices, when coupled with turboshaft engines and modern fuselage designs, has produced dash speeds of nearly twice those of conventional operational helicopters.

This paper will show how programmed pilotage can be used to further increase the high speed capability of rotorcraft. The parameters of concern are rotor RPM and wing lift.

To ensure the success of any hardware system, it must possess either commercial or military potential. Design considerations have generally precluded mixing of the roles, with the exception of transport

vehicles and limited electronic systems. Outlined below are two sets of problems which could be attacked by a compound rotorcraft such as now envisaged.

A. COMMERCIAL AVIATION

With the increased growth of population centers, traffic congestion has led to increased "center to center" travel times for trips of less than 1,000 miles. For example, the average speed by air between downtown New York and downtown Washington, including baggage claim, taxi rides and holding patterns, is only slightly greater than could be achieved by train or automobile: 70 MPH vice 50 MPH. The same problem holds in travel between London and Paris and many other large population centers. Conventional helicopters have shown their value in some of these areas but, with cruise speeds only about twice that of ground transportation, the expense of operation has precluded profitable passenger operation except in a few places.

With a speed capability in the neighborhood of 300 Kts, the "break even" point would occur with fewer passengers and/or would make longer flights profitable. Such usage would also eliminate a great deal of traffic congestion in the neighborhood of metropolitan airports.

Of concern to passengers and to citizens in the flight path of any aircraft are safety and noise. Both of these factors will be discussed later.

B. MILITARY APPLICATIONS

The mission capabilities of such a machine vary throughout the entire range of present helicopter roles. Some, such as external hoist (crane) operations, mine sweeping and plane guard, would receive no benefit from improved dash speed capability.

At the other end of the spectrum, particularly in a hostile environment, attack, search and rescue (SAR), medical evacuation and missile launching fleet defense missions would reap enormous benefits. While some of these missions overlap with those flown by fixed-wing airplanes, the SAR mission in hostile territory has been relegated to the hover-capable (and up until now, extremely vulnerable) helicopter of conventional design. It is with this fact in mind that an ultra-fast rotorcraft is now conceived as a straightforward design project.

II. DESIGN PROBLEM

The design of a high-speed vehicle capable of adequate hover capability is a classic example of compromise. In general, those characteristics which improve the performance in one mode of flight degrade it in the other.

Attempts to produce high-speed rotorcraft with hover capability have met with varying degrees of success in the past. Below is listed a brief review of each of the approaches attempted and a discussion of the capabilities of each type of machine.

A. TILT WING AND TILT ROTOR

These types have been quite successful but suffer from bulky and complex transition equipment. Wing or rotor tilt failure usually precludes a landing in the conventional manner due to blade clearance. Some work has been done with ducted fans and at present seems to provide some hope.

An interesting pioneer effort was the XVIA 'Pogo Plane' which took off vertically from its own tail. The initial transition from vertical to horizontal flight was not difficult, but the transition back to vertical flight with the wing fully stalled, nose pointed skyward, must have been an unnerving experience. The control problem in this type of vehicle is normally handled by use of multiple rotors which, of course, add drag and require more power.

B. DIRECT JET LIFT

The direct-lift method leaves the top end of the speed regime open but at the expense of hover capability. Two distinct methods of lift production are possible. One utilizes vectored thrust from the vertical flight engines that also produce thrust for flight. This is the approach utilized in the Hawker-Siddeley "Harrier." A second method utilizes two distinct engine systems, one for lift and a second for thrust. The advantage of this type lies in a simpler transition from hover to forward flight. This could lead to a weight penalty in that some engines will normally be producing little or no thrust during part of the flight. However, the thrust vector baffles, servos, and controls which are necessary in the other system are not required in this system.

All jet-lift vehicles so far produced suffer severely from limited hover capability in that noise levels and fuel consumption are both very high. The vertical flight mode can practically be used only for take-off and landing and thus limits the mission capability of such machines. High downwash velocities, high exhaust gas temperatures and a low hover endurance all act to limit the value of this approach in high-speed rescue vehicles.

Control systems must necessarily be duplicated, i.e., there must be one for the hover mode, generally of the vectored thrust type, and a second of the conventional fixed-wing type. Further, failure of an engine in the hover can only lead to disaster unless a sufficient number of engines are provided.

C. THE STOWED ROTOR CONCEPT

Some day the stowed rotor machine may provide the forward flight characteristics of the fixed wing airplane and the vertical flight capability of the helicopter. There is currently much research being conducted in this field but, as yet, it is not an engineering problem. Flutter, divergent flapping of rotor blades during rotor shut-down, duplication of control systems, reliable blade fold sequencing, CG shift and other problems face the development of this machine.

It appears that this will not be a next generation VTOL aircraft, but will undoubtedly play an important role if and when the technical difficulties are overcome.

D. THE COMPOUND HELICOPTER

The compound helicopter is limited in top speed but possesses good hover performance. The usual complexities of conventional helicopters exist but the state of the art has progressed to the point where these problems are minimal and, presupposing sound engineering practices and design, the hardware concerned is straightforward and reliable. Such machines have years of experience and application in their background.

In designing the next generation VTOL aircraft, consideration should be given to the straightforward engineering approach to the problem. By building on past experience and employing a few new concepts, a VTOL aircraft capable of turbo-prop airplane speeds and good hover performance can be built based on current technology.

III. DESIGN APPROACH

Previously, helicopters have been designed to hover and airplanes to fly forward. The results have been helicopters with poor forward flight capabilities. Little effort has been expended on streamlining until fairly recently. Notable exceptions include the Fairey Rotodyne (which flew 200 MPH regularly) and the AH-56 Cheyenne, Lockheed's attack machine.

Incredibly, flush riveting, retractible landing gear, full canopies and faired rotor heads have received almost no attention in the past. Flat plate areas have been reduced by nearly 50% by clean-up programs on the S-67 helicopter over the S-61 which share the same rotor/power train.

While such efforts are admirable, flat plate areas of under 12 sq. ft. are only targeted for helicopters. The Fairey Rotodyne (11.0 sq. ft.) was cleaner than what is presently being approached. The difference lies in the fact that this machine was designed as an airplane which could hover rather than as a helicopter which could fly forward.

In compound helicopters, which keep their fuselages substantially level in forward flight, low flat plate areas are maintained throughout the speed range, unlike the pure or vectored-thrust helicopter which requires its fuselage to be tilted forward progressively with forward speed, thereby converting what is intended to be of streamline shape

into a bluff body. The parasite or body drag of pure helicopters is therefore detrimental to high speed capability.

A. INITIAL DESIGN PARAMETERS

Configuration: Single main rotor. Torque compensation by dual outboard propellers mounted on stub wing tips. Dual turbo-shaft engines.

Maximum overgross weight in hover-out-of-ground-effect, at Sea Level standard conditions: 20,000 lb.

Rotor Diameter 50 ft. based on the following:

a. Shipboard stowage limitations

b. Disk loading of about 10 lb/ft^2

Maximum Forward Speed at Sea Level 280 Kts.

B. FORWARD FLIGHT SPEED LIMITATIONS

Under ideal conditions for peak speed, the blades would be simultaneously reaching shock stall conditions on the advancing blade, tip stall on the retreating blade and maximum power, provided the power required is greater than that required to hover under design conditions.

Figure 1 shows the flight envelope for the aircraft, flight being possible within the large triangular areas bounded by lines of constant tip-speed ratio and constant advancing blade-tip Mach number [Reference (3)].

Steady state flight has been achieved with tip-speed ratios (μ) greater than unity, but the system is extremely susceptible to flutter. Since periodic torsional moments due to center of pressure shift are present, the torsional stiffness would have to be greatly enhanced if μ over 0.9 were utilized.

Advancing blade-tip speeds of the order of Mach 0.98 have been achieved but such speeds are not to be expected under other than ideal conditions. Advancing tip speeds of the order of Mach 0.95 can be expected to produce minimal shock stall, particularly if the blade tips are of reduced thickness and swept as in the UH-1 "Huey-Plus" and S-67 "Black Hawk."

The above speed limitations are based on rotor aerodynamic properties. Given a clean airframe and ample power, a rotor aircraft can fly operationally at 300 MPH.

Essential flight instruments in such an aircraft would include a blade-tip Mach probe on which the pilot could read maximum tip Mach number and a "Mu gage" which would simply compare the aircraft Mach number with the maximum blade tip Mach number. Engine speed can be altered to maintain constant tip speed at higher airspeeds. When the maximum "μ" value is obtained, at maximum tip Mach number, "Red-Line" would be reached for the given density altitude conditions. Computation of rotor tip Mach number based on fuselage Mach number and rotor tachometer output could similarly be used as the governing signal.

Flight data might enlarge the envelope and increase the top speed if the tip-speed ratio could be increased without undue stress on the airframe and rotor system.

C. TORQUE COMPENSATION

The torque supplied to the rotor system by the engines, through the transmission, in powered flight must be balanced by an equal and opposite torque applied by some other device. Several methods have been employed in the past, including:

1. A second counter-rotating rotor, mounted above, beside or behind and either intermeshing with or clearing completely the first rotor.

2. Adoption of a thrust device with axis perpendicular to that of the main rotor and offset by some distance. The tail rotor and offset thrust rotor are examples of this type.

The torque problem can likewise be avoided by use of a self-propelled rotor utilizing pressure jets or ramjet engines mounted at the tips. Both of these methods eliminate all torque except that owing to the friction of the rotor shaft, which is very small. Further, the transmission system can then be eliminated, cutting cost, weight and complexity. The disadvantage of such systems includes high fuel consumption rates and high noise levels while the rotor is loaded.

The Fairey Rotodyne, a relatively sophisticated compound rotorcraft, utilized a pressure jet rotor of 90 ft. diameter. The aircraft

performed very well and held the world's rotorcraft speed record at something over 200 MPH in 1957. The noise problem, however, forced the end of development on the aircraft. At a gross weight of 60,000 lb., the disk loading of the Rotodyne was 9.4 lb/sq. ft., or slightly less than that of the machine proposed here, indicating that the pressure jet or the less efficient and noisier ram jet system would be unacceptable in the proposed aircraft.

The alternatives remaining open include only those applicable to a single-rotor design. The high-speed capability of any aircraft is seriously hampered by the addition of a rotor. Multiple rotor designs are less efficient at high speeds than single rotors, owing to their drag. A possible exception is Sikorsky Aircraft's proposed Advancing Blade Concept (ABC) which utilizes a coaxial rotor arrangement of very stiff, small-diameter rotors operating at very high tip-speed ratios. This approach, while interesting and perhaps promising, remains to be proven in flight.

The tail rotor is a proven method of providing both yaw control and torque compensation throughout the flight regime of the single-rotor helicopter. Pioneered and perfected by Sikorsky, it is a reliable system capable of producing high torque values with relatively little power drawn away from the main rotor owing to its large moment arm. With a stable fuselage, however, aerodynamic stiffness of the aircraft in yaw can balance rotor torque. Thus, in a properly designed compound machine at high speed, the wings unload the rotor, reduce the rotor

torque (and hence the required counter-torque) and the tail rotor becomes an aerodynamically inefficient rudder which degrades performance.

Ducted tail rotors and variable vanes in propeller slip-streams have met with limited success. Piasecki Aircraft has attempted the latter vectored-thrust method in a research aircraft. The obvious advantage of this system is that the vectored thrust can overcome torque in low-speed flight and drag in high-speed flight. This leads to the offset thrust rotor system adopted for use in the present design study.

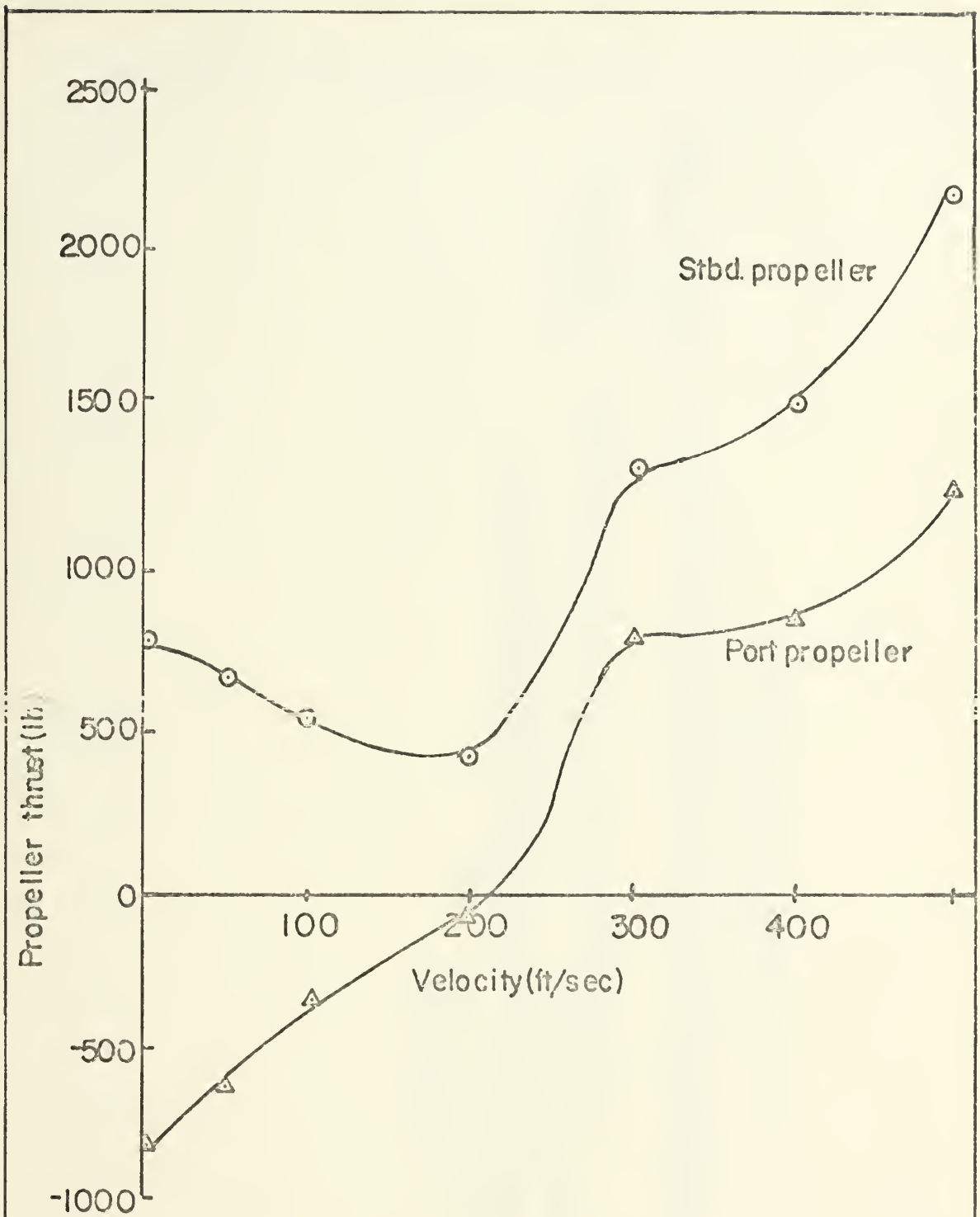


Fig. 3. Propeller Thrust Requirements
at 20,000 lb. at Standard Sea Level Conditions

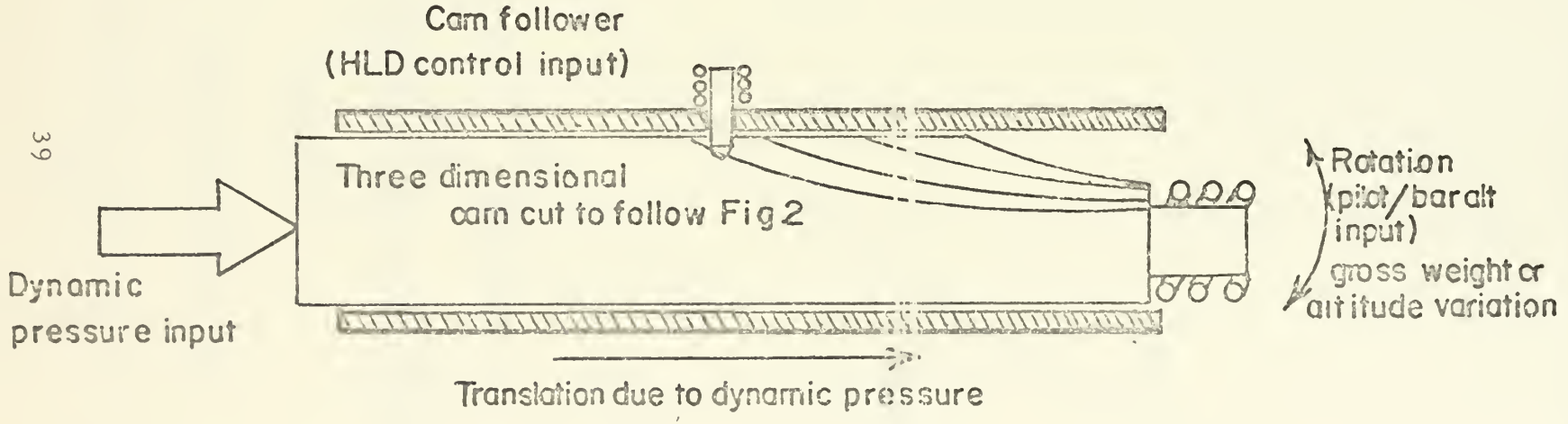


Fig. 4. Mechanical Analog for High Lift Device Control

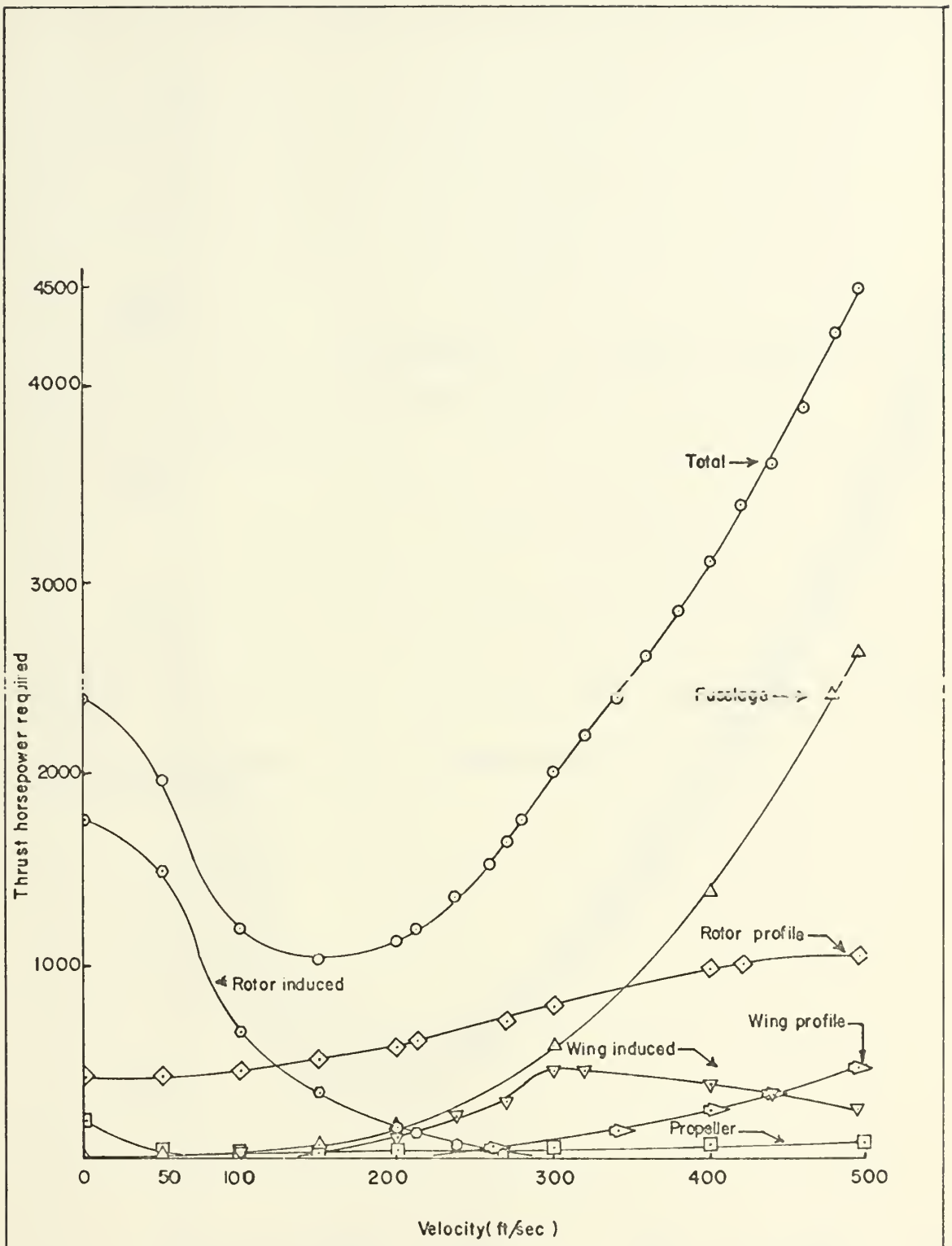


Fig. 5. Drag Power Components

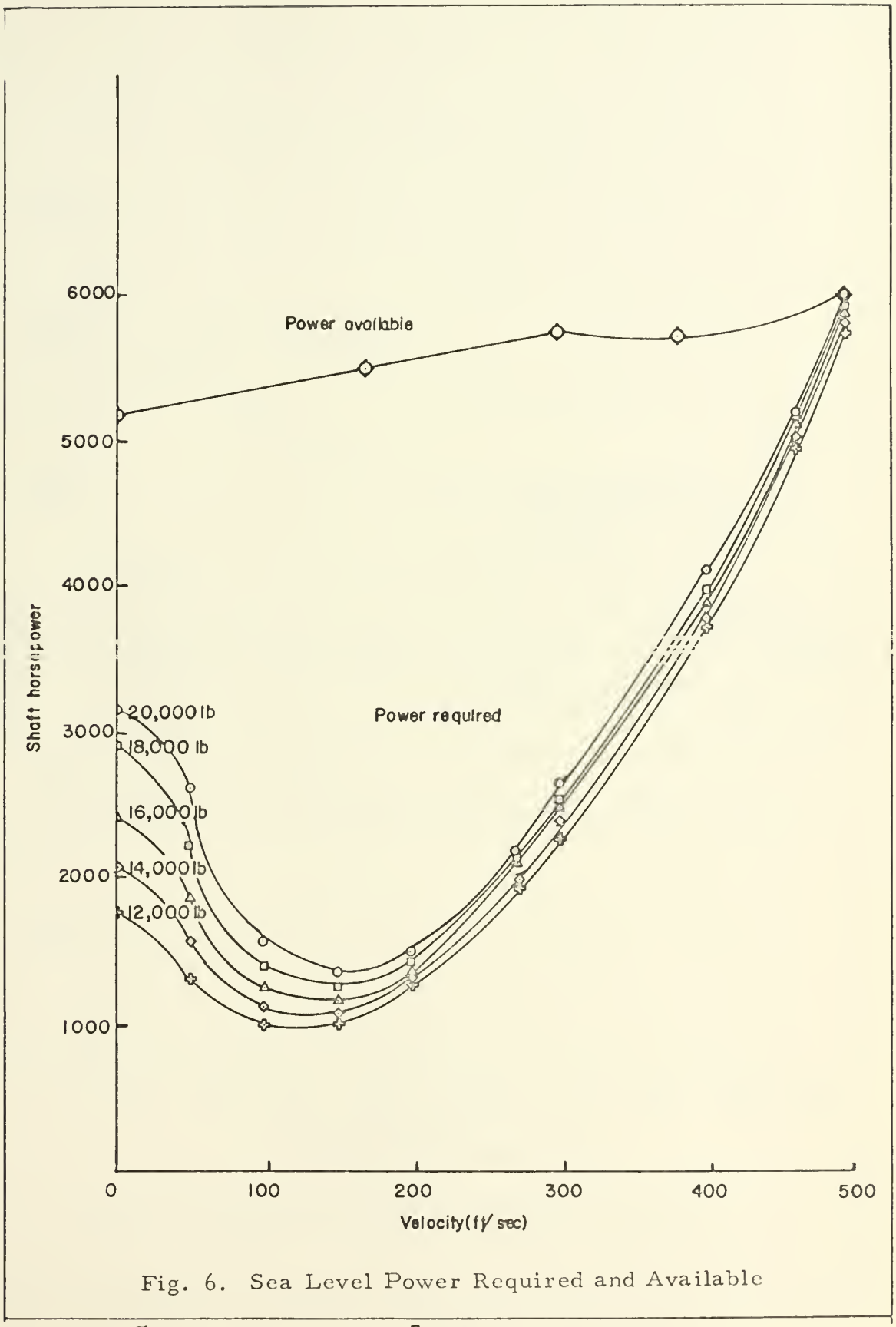


Fig. 6. Sea Level Power Required and Available

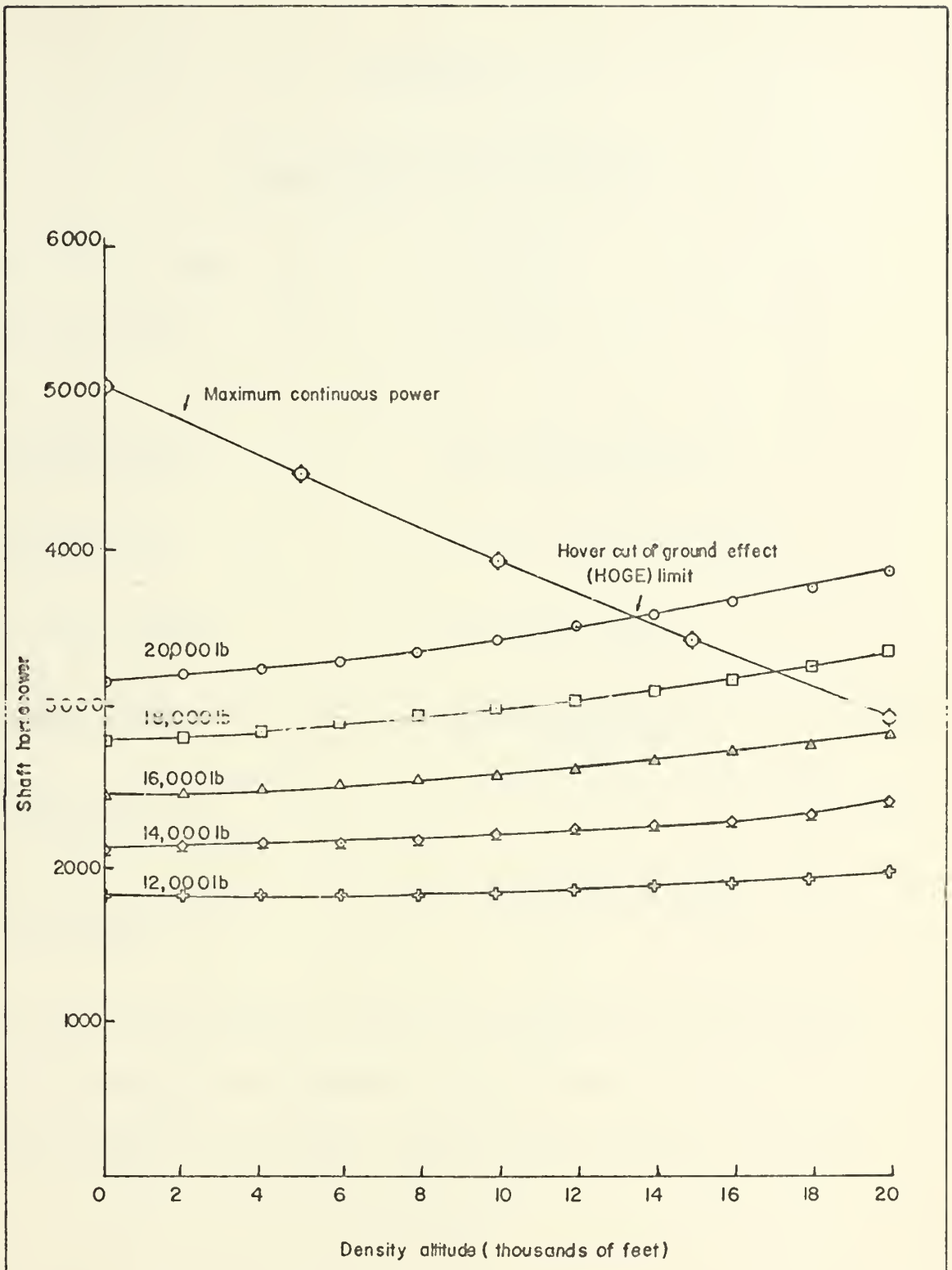


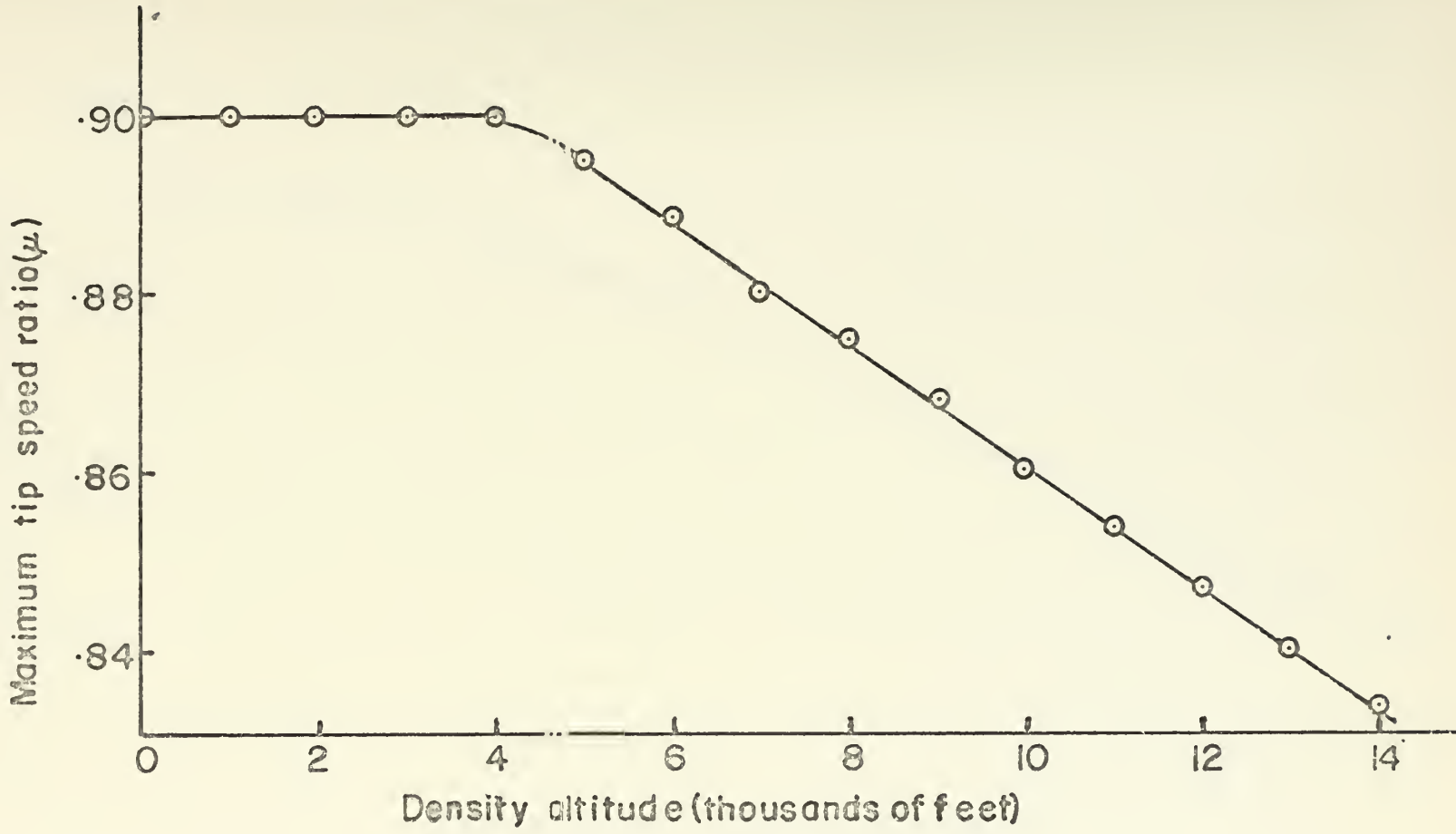
Fig. 7. Hover-Out-Of-Ground-Effect Performance

APPENDIX A

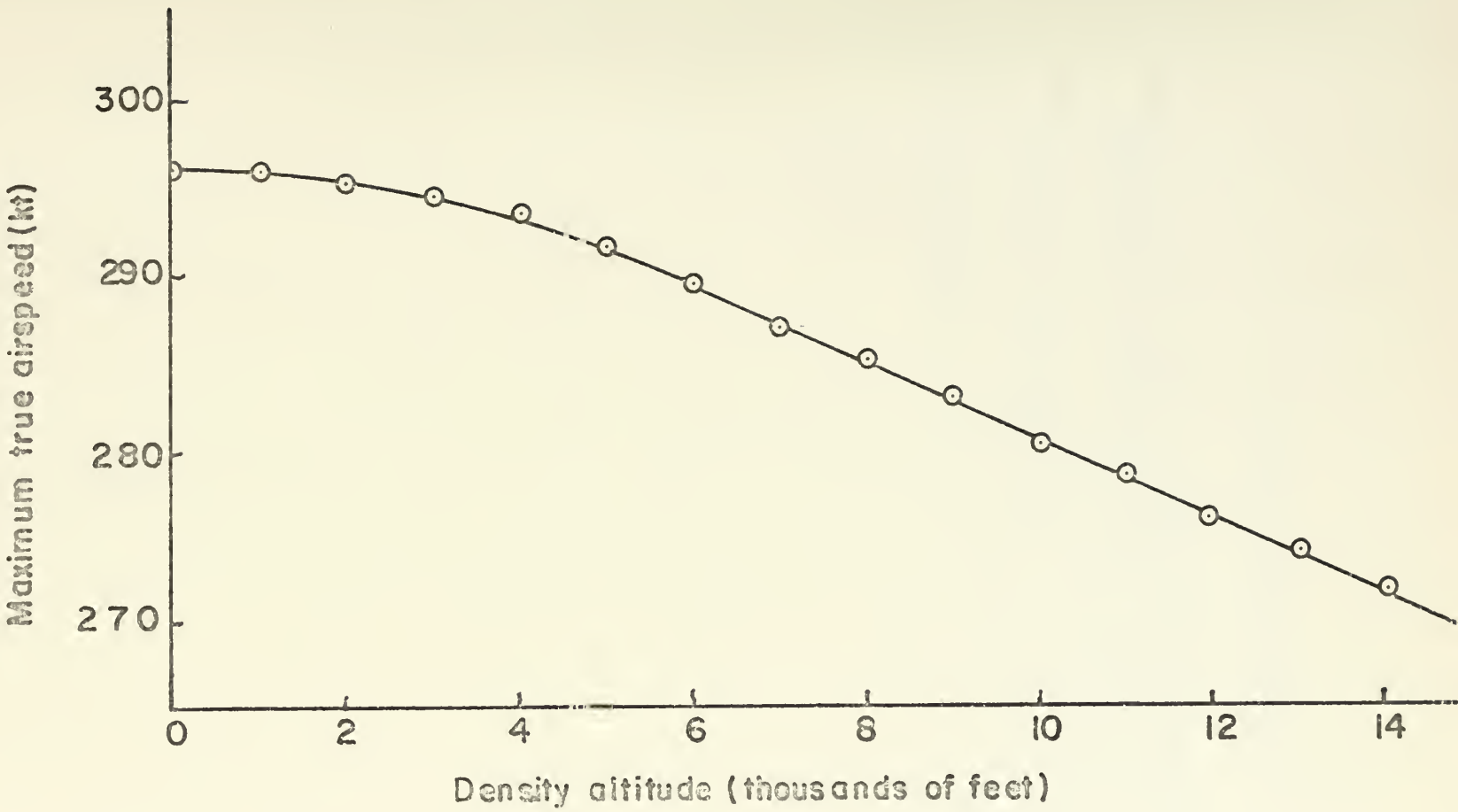
COMPUTED PERFORMANCE

Initial Gross Weight	20,000 lb.
Initial Fuel Load	8,000 lb.
Crew	3
Max Ferry Range (SFC=0.70)	1500 statute miles at 130 kts TAS (initial)
Max Endurance (SFC=0.70)	16 hrs at 60 kts (initial)
Max Range (DASH) (SFC=0.70)	820 statute miles
Max Dash Speed	296 kts TAS at Sl.
Max Hover out of Ground Effect alt. at Max gross weight	13,500 ft DA
Max Rate of Climb at Sea Level	5,700 ft/min (initial)

Optimum Mission Profile: Launch, fly 260 nautical miles at 280 kts to rescue area, hover 15 minutes, recover four survivors and return to base with 10% fuel reserve. Mission elapsed time 2-1/4 hours.



Appendix A. Variation of Maximum Tip Speed Ratio with Density Altitude



Appendix A. Optimum Speed Performance at Altitude

LIFT OF REFERENCES

1. Segner, Wyrick and Blay, Flight Characteristics of a Compound Helicopter, Lockheed Horizons, Issue 2, 1965.

2. Gessow and Meyers, Aerodynamics of the Helicopter, Ungar Publishing Company, New York, 1952.

3. Engine Test Report, Allison Model 250-C-18 Turbo Shaft Engine, 1 April 1966.

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